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**13. ABSTRACT (Maximum 200 words)**

Cellular Nonlinear Networks (CNNs) are large arrays of nonlinear circuits coupled to their immediate neighbors. During the past three years, while partially funded by this grant, graduate student Kenneth R. Crounse, working with the the principle investigator and their associates, have made many advances in understanding the dynamics of such arrays, especially their spatial pattern forming properties and the generation of spatial disorder.

Pattern formation in CNNs was found to be amenable to analysis by the Turing instability and synergetics paradigms. Both of these methods are widely used to explain phenomena in physics and biology, some of which have been demonstrated on the CNN (e.g., angelfish stripes). In addition, interpreting the CNN behavior in terms of the synergetics paradigm was shown to be useful for the design of some CNN image processing templates (e.g., fingerprint enhancement).

We have also developed a general method for the implementation of general Cellular Automata on the CNN Universal Machine. Cellular automata can be used as models for many complex physical systems. In particular, we have investigated methods for producing disorder through reversible gas-like automata. Some applications being explored are random number generation and cryptography.

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# Pattern Formation

Many systems have been studied as models for spatial pattern formation in biology, chemistry and physics. The types of systems we are interested are those that consist of a large number of 'cells' in a regular array. The state of each cell represents an important quantity, such as a chemical concentration or a magnetic spin direction, and changes in time according to a rule which depends on the state of the cell's neighbors. The primary example is the reaction-diffusion system used to explain symmetry breaking in biological growth. Other examples include cellular automata models for Ising spin glass systems and spatially coupled differential equations and maps for binary alloys. These systems can produce some very qualitatively similar output, suggesting a common underlying mechanism. We have used the CNN paradigm, which has a more general and accessible parameter space, to demonstrate principles which lead to such patterns and to study what types of patterns are possible.

A theoretical generalization of these paradigms was developed for the CNN which can be used to predict the pattern formation properties of given templates, based on the Turing instability approach and the synergetics paradigm. It is our opinion that the Cellular Neural Network model provides a superior method to control the critical instabilities needed for pattern formation without obfuscating parameterizations, complex nonlinearities, or high-order cell states, which allows a general and convenient investigation of the essence of the pattern formation properties of these systems.

## Turing Instability

We have found that the Cellular Neural Network can produce patterns similar to those found in Ising spin glass systems, discrete bistable systems, and the reaction-diffusion system. In our study, we did not restrict the coupling between cells to be with immediate neighbors only or to have a special diffusive form. When larger neighborhoods and generalized diffusion coupling is allowed, it was found that some new and unique patterns can be formed that do not fit the standard ferro-antiferromagnetic paradigms.

We found that the first order CNN can exhibit the critical spatial frequency instability around the equilibrium required for Turing pattern formation. This is analogous to a one-morphogen or single-layer reaction diffusion system, which can exhibit the critical instability when negative or larger diffusion matrices are allowed. The CNN presents a natural way to study generalizations of diffusion and what types of instabilities are possible. In addition, the simple saturation nonlinearity of the CNN locally enforces a frequency-phase separation which is found in many real pattern forming systems.

Our research has led us to identify the following three epochs of behavior in the time formation of patterns which are generated by random perturbations about the unstable equilibrium.

1. Linear System leading to noise shaping. If the system is halted at the moment when the first cell of the array enters the saturation region, the linear system theory will be exact. The states at this time will be the result of a linear filtering operation which can be found in terms of the template weights. Such a filtering operation can be understood to enhance certain spatial frequencies while suppressing others.

2. Separation of Spatial Frequencies and Phases leading to meta-stability. In regions where a significant number of cells have reached saturation, the linear analysis does not even hold approximately. At this point, arbitrary combinations of the unstable modes can no longer be

maintained. The states begin to separate themselves into regions with motifs that are at least locally stable. These regions grow until their boundaries meet with other regions of different motif. At this point the system is considered to be meta-stable in the sense that most cells are unchanging in time (the interior cells of the regions) and only the boundaries between regions are moving.

3. Boundary Negotiation leading to stability. Even though the array has separated into regions that are locally stable, the boundary between them may prove to be unstable. Thus begins a long process where most of the cells in the array are not changing in time, but slowly the boundaries are negotiated. In some cases there may not be any acceptable boundary, and eventually one motif must cover the whole array. The whole process may take many order of magnitudes longer than the first two steps.

The simple form of the CNN nonlinearity allowed us to observe a more defined distinction between the growth due to linear instability in the linear region and phase/frequency separation and boundary negotiation in the saturation region.

We have also investigated the patterns formed from site defects and irregular array boundaries.

## Synergetics

The study of the spontaneous self-organizing behavior of collections of locally coupled systems is known as synergetics. The name comes from the idea that cooperation between simple systems can produce a large-scale order. Synergetic mechanisms have been found to be useful for explaining phenomena in physics, chemistry, and biology. In addition, an understanding of these mechanisms has been applied to problems in computer recognition of human faces under the philosophy "Pattern Recognition as Pattern Formation".

The principle ideas from synergetics, as promoted by H. Haken, are as follows: First, a synergistic system, when linearized about an unstable equilibrium, can be characterized in terms of stable and unstable modes. Small perturbations about the equilibrium will excite these modes. The unstable ones will begin growing while the stable ones diminish. The stable modes can be found to be 'slaved' to the unstable ones. That is, the dynamic trajectory of the stable modes will not depend on the perturbation in the stable direction but can be written solely in terms of the unstable modes. Second, the nonlinearity will eventually promote a competition among the unstable modes for dominance. The relative strength of the unstable modes are known as order parameters since they solely determine the type and amount of organization in the equilibrium.

We have shown that the nonlinear array dynamics of the simplest Cellular Neural Network (CNN) exhibits the basic phenomena of 'synergetics'. We have investigated how the computation performed by physical synergetic systems could be emulated in a natural way on the CNN to perform useful image processing tasks. Namely, the physical phenomena can be interpreted in terms of linear spatial filtering and morphological constraints. The classical CNN 'averaging' template has been interpreted in this light and, informed by the synergetics interpretation, improved for a particular example. We have also investigated applications to fingerprint enhancement and strong feature detection.

# Spatial Disorder

## Cellular Automata

The cellular automata are a class of dynamical systems which are discrete in state, space, and time. The states of a cellular automaton evolve synchronously according to a state transition rule which operates within a local neighborhood of some radius of the state being updated, typically in a time and space-invariant manner. The order of the CA is the number of previous times the states are required to computed the next state.

We have given a general constructive proof that the CNN Universal Machine architecture can directly implement arbitrary first-order cellular automata. Past approaches have used either discrete time operation and complex nonlinearities, multiple layers, or time varying templates. By using the CNN Universal Machine architecture, we show that these complications are unnecessary. In addition, we have also shown that a particular and useful class of reversible second-order CA can be implemented on the CNNUM.

## Random Number Generation

High-speed high-quality reproducible random number generation is a significant problem, with many applications ranging from simulation of physical systems to cryptography. We have demonstrated that the CNN Universal Machine (or the Discrete-time CNN) is capable of producing a two-dimensional pseudo-random bit stream at high speeds by means of cellular automata (CA) We investigated methods for random number generation on the CNNUM with two reasons in mind: First as a native source of good random numbers for use in CNNUM algorithms for such areas as image processing and modeling physical systems, and second as a basis for implementing exceptional, and possibly novel, cryptographic algorithms. However, there are many potential uses for a CNN based pseudo-random number generator, for instance, random location selection, annealing algorithms, image dithering and quantization, stochastic resonance, Gaussian noise generation and spread spectrum communications.

The first random number generation schemes which we developed for the CNNUM were based on irreversible two-dimensional CA rules and were analyzed by a battery of statistical tests as well as mean-field theory. Second, a special class of reversible second-order CA, which are also easily implemented on a CNNUM, were considered for random number generation and were shown to have some desirable properties. These second-order reversible CA exhibit gas-like behavior.

The randomness of CA have been investigated in other places, but have only been well-analyzed for a certain one-dimensional rule. Some two-dimensional CA have been noted to be random, but have not been sufficiently analyzed. Our findings indicate that the two-dimensional CA show great promise as random number generators.

## Cryptography

Finally, as an example application for random number generation on the CNNUM, some cryptographic schemes were proposed. Due to its massive parallelism, the CNNUM offers the possibility of high speed cryptography while offering very large ($> 1000$ bits) key space.

Perhaps the simplest use of CNN-based pseudo-random bit generation for cryptographic purposes is in a key stream cipher. In this scheme, a stream of 'random' bits from a *key stream generator* is used to encode the plain-text data stream bit-by-bit by applying an XOR operation (which is invertible) between them. At the receiver, the same sequence of bits produced by an

identical key-stream generator is then used to decode the plain-text. Security is provided by the use of a key, which is a shared secret, to somehow affect the bit-stream produced.

Another possibility is the block cipher, which transforms blocks of the plain-text during encryption. This type of approach has many advantages including the facts that the sender can easily mix random data into the plain-text stream so that sending the same message will result in a different cipher-text and the key or key stream is not easily found through a plain-text attack.

In our proposed block encryption scheme, under investigation, we use the reversible CA as the basis for the algorithm. The initial states $s(-1)$ and $s(0)$ are set to be an arbitrary random image and the data image respectively. Then, the CA is run for a previously defined number of steps, $N$, and $s(N-1)$ and $s(N)$ are transmitted. The trick is to introduce some secret (shared) information into the CA dynamics. This could be many different things including switching between CA rules according to a secret ordering, flipping state bits in certain secret places and times, or specifying boundary value information. The receiver can then run the CA system backwards to recover the initial data.

## List of Publications


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